MEDIATED MODELING IN SCIENCE EDUCATION

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Following two decades of corroboration, modeling theory is presented as a pedagogical theory that promotes mediated experiential learning of model-laden theory and inquiry in science education. Students develop experiential knowledge about physical realities through interplay between their own ideas about the physical world and particular patterns in this world. Under teacher mediation, they represent each pattern with a particular model that they develop through a five-phase learning cycle, following particular modeling schemata of well-defined dimensions and rules of engagement. Significantly greater student achievement has been increasingly demonstrated under mediated modeling than under conventional instruction of lecture and demonstration, especially in secondary school and university physics courses. The improved achievement is reflected in more meaningful understanding of course materials, better learning styles, higher success rates, lower attrition rates and narrower gaps between students of different backgrounds

KEYWORDS:
Experiential learning, learning cycle, mediation, model, modeling inquiry, paradigm, schema

KUNNING HEAD:
Mediated modeling

The pivotal role played by models is increasingly recognized in scientific theory and inquiry, most importantly in human cognition in general and in science education in particular. In science, models are considered principal means, if not *the* chief ones, with which scientists: (a) represent, investigate, control, and impose order on, physical systems and phenomena, and (b) put together scientific theory coherently and corroborate it efficiently (Bunge, 1967; Giere, 1988; Harré, 1970, 1978; Hempel, 1965; Hesse, 1970; Wartofsky, 1968). Some cognitive scientists have argued that model construction and deployment are not restricted to science, and that these activities extend to all sorts of human endeavors (Bower & Morrow, 1990; Gentner & Stevens, 1983; Giere, 1992; Johnson-Laird, 1983; Lakoff, 1987). In science education, calls have subsequently reverberated to align science curricula with the content and practice of science, even with natural human thought, by engaging students in model-based learning and inquiry. In this respect, models emerge as effective pedagogical tools for helping students evolve into the realm of science and develop the sort of scientific literacy that prominent organizations like AAAS (1990, 1993), AAC&U (2002), NRC (1996) and NSTA (1995) have been advocating (Bullock, 1979; Casti, 1989; Clement, 1989, 1993; Doerr, 1996; Erduran, 2001; Gee, 1978; Giere, 1994; Gilbert, 1991; Glas, 2002; Hafner & Stewart, 1995; Joshua & Dupin, 1989, 1999; Justi & Gilbert, 2002; Moreira & Greca, 1995; Nersessian, 1995; Passmore and Stewart, 2002; Redish, 1994; Shore et al., 1992; Smit & Finegold 1995; Steen, 1990; Viau, 1994; White, 1993; Windschitl, 2004). This article is the culmination of over two decades of model-based research and instruction into which this author has been engaged, in cooperation with many educators based mostly in USA and Lebanon. It presents an overview of what experiment and experience have shown to be efficient teaching practice in bringing about meaningful learning of science, especially in secondary school and university physics courses (Halloun, 1984, 1994, 1996, 1998a, 2000, 2001a, 2003, 2004a; Halloun & Hestenes, 1987).

The last two decades have witnessed, worldwide, a plethora of reform movements in science education. Some reform efforts concentrated on course content, while others overwhelmingly focused on learning styles and teaching methodology. At the level of course content, innovations went from: (a) the development of supplementary tools for structuring existing materials like concept maps (Novak, 1990), Vee diagrams (Novak, Gowin & Johansen, 1983), and semantic networks (Fisher, 1990; Goldberg, Bendall and Bach, 1991), to (b) fundamental restructuring of course content on new foundations like in the case of Reif's hierarchical organization (Eylon & Reif, 1984; Reif & Allen, 1992; Reif & Heller, 1982). At the level of learning styles, the spectrum extended from getting students engaged in: (a) autonomous activities that are virtually free from all constraints (e.g., radical constructivism) to (b) structured activities that follow specific guidelines and sequences like in the case of Karplus' learning cycle (Karplus, 1977). Teachers' involvement has been marginal at the former end of the spectrum. It took many forms, elsewhere, extending from: (a) inducing a cognitive disequilibrium for subsequent self-regulation à la Dewey or Piaget, sometimes through Socratic dialogues (Hake, 1992; Raman, 1980), to (b) modeling experts' behavior through cognitive apprenticeship (Heller, Foster & Heller, 1997; Shore et al., 1992). While all these efforts have been deployed in various directions, we were working, and still are, on developing modeling theory as a pedagogical theory that attends to the two broad concerns in science education: (a) *what* a science course should consist of, and (b) *how* teacher and student may go about fulfilling course requirements in the most meaningful, equitable, and efficient way possible.

Our analysis of the literature in the history and the philosophy of science and in cognition and science education, and our long years of practice have led us to the following tenets (Halloun, 2001a, 2004a):

1. No pedagogical theory can bring about meaningful learning of science unless it is about both how a science course should be structured and how it should be taught and learned.
2. Student evolution into the realm of science may be efficiently realized through a learning process that somewhat recapitulates the historic development of scientific paradigms. Most students come to secondary school and university education with knowledge about the physical world and science governed, in many respects, by the sort of naïve realism that dominated the pre-Galilean era. This knowledge may be regulated in harmony with modern scientific realism by guiding

students through the sort of successive refinements of model-laden theory and inquiry which Galileo and his successors went through.

3. For meaningful learning of science, students need to systematically engage in identifying and modeling physical patterns and explicitly structure any scientific theory around a well-chosen set of models. To this end, students need to be empowered with appropriate scientific and cognitive tools and rules, and engaged in model construction and deployment activities that are systematically diversified and designed so as to cover fundamental aspects of empirical-rational dialectics that characterize scientific inquiry.

4. For efficient learning, teachers need to put together and forth coherent and systematic lesson plans that are flexible enough to accommodate both scientific rigor and pedagogical concerns. They need to put such plans into effect with active student participation, and mediate learning activities in a variety of modes so as to help individual students continuously evaluate and gradually regulate their personal knowledge.

These four tenets are actually basic premises of a pedagogy which we subscribe to, pedagogy that is primarily grounded in modeling theory. Modeling theory is originally a theory of science, a theory about scientific theory and practice, that is advocated by philosophers of science and cognitive scientists and that we are extrapolating into science education (Halloun, 2004a). This article outlines fundamental aspects of what we hope will evolve into a full-fledged *modeling theory of science education*. These are foundational aspects that pertain primarily to the last three points above and that have been corroborated through our research and practice in the last two decades, especially in secondary school and introductory university (college) physics courses. The article is thus a theoretical overview of the pedagogical modeling theory. Supporting research and explicit instructional guidelines in specific contexts are presented elsewhere (Halloun, 1984, 1994, 1996, 1998a, 2000, 2001a, 2003, 2004a; Halloun & Hestenes, 1987).

We begin our discussion with the second point above bearing on the lessons we learn from the history of science about science education. We then show how these lessons and others from cognitive science served us in the development of modeling theory in science education along the lines of points 3 and 4 above. More specifically, we discuss how to put together the content of a scientific theory around a few basic models (section 2 of the paper) of well-defined structure (§ 3) following specific modes of modeling inquiry (§ 4). We then discuss how students can be empowered to develop model-laden theory and inquiry skills through student-centered, teacher-mediated (§ 5) learning cycles (§ 6). We end our discussion with a brief overview of what science instruction following the advocated approach actually leads to in the classroom, especially in physics courses at the secondary school and college levels (§ 7).

1. HOW SCIENCE EDUCATION MAY RECAPITULATE THE HISTORY OF SCIENCE: A REALISTIC BACHELARDIAN-GALILEAN PERSPECTIVE

Educational research has systematically shown in the last three decades that individual students bring to their secondary school and college science courses a heterogeneous and loose mix of ideas about the universe and about inquiry in the physical world. Some of these ideas may be somewhat compatible with scientific paradigms, others at odds with such paradigms and reminiscent of pre-Galilean paradigms* (Cobern, 1993; Halloun, 1986; Halloun & Hestenes, 1985a, 1998; Helm & Novak, 1983; Novak, 1987, 1993). Concerned scholars have subsequently turned to the history of science in order to better understand the foundations of student thinking and identify historical cases that may be deployed in educational settings for regulating students' knowledge. In line with this perspective, we believe that student knowledge can be better understood, and its evolution efficiently tracked and directed, if: (a) we systematically characterize such apparently incoherent knowledge by drawing on major historical paradigms and cognitive science, and (b) focus on critical turning points in the history of science that may be efficiently recapitulated in educational settings for helping students evolve into the realm of modern science. The works of Gaston Bachelard and Galileo Galilei were for us the most enlightening in this direction.

Any person's ideas about physical realities (systems and phenomena), and the ways the person go about interacting with such realities can, for us, and in accordance with Bachelard (1940) and Mortimer (1995), be conveniently organized into what we call a *paradigmatic profile*. A paradigmatic profile consists primarily of a number of paradigms that may not be necessarily fully developed and that may or may not be compatible with one another. Various components of a paradigmatic profile may be at different levels of maturity and complexity depending on the individual's personal experience. A given conception (concept, law or any other theoretical statement) may be confined to a single paradigm, or it may have different alternatives distributed across different paradigms (Halloun, 2004a).

The paradigmatic profile of a modern day scientist is dominated by two broad dimensions, i.e., two broad paradigms, one governed by *classical* scientific realism (CR), the other by *modern* scientific realism (MR). We speak of scientific *realism* because scientific conceptions *correspond* to physical realities, and each conception *represents* a set of these realities in specific respects and to a certain extent. This does not ignore the fact that scientists invent their conceptions (just like ordinary people do) in order to *re*construct, in a convenient way, what they represent in the real world. The viability of each dimension (CR or MR) is well established by a concerned scientific community within well-defined scopes and limits of approximation and precision, and the two dimensions complement one another in specific respects. A physicist may use a Newtonian model (from a classical paradigm) to study the motion of a given physical object, and then shift to a relativistic (modern) model to study the same motion or a similar one should s/he desires to significantly improve the precision of the outcomes. In contrast, paradigmatic profiles of ordinary people, science students of all levels included, do not have their scopes and limits of viability well delineated, and various paradigms often overlap one another in conflicting ways. A student might have recourse to a particular model when studying a given movement (say, a positivist model), and then to a contradictory model (say, a classical, Newtonian one) when dealing with a similar movement actually governed by the same model from a scientific perspective.

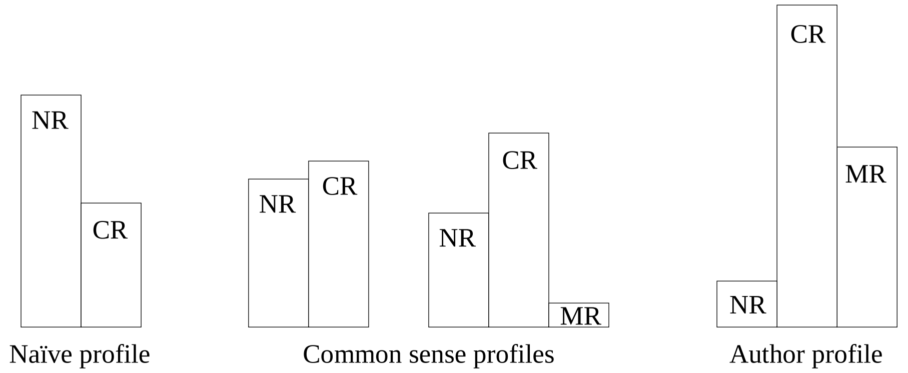


Figure 1. Paradigmatic profiles (Halloun, 2004a).

Bars are not to scale in the above bar charts, and bars' relative heights reflect an ordinal and not a proportional order of magnitude.
My own natural paradigmatic profile is currently dominated more by classical scientific realism (CR) than by modern scientific realism (MR) because my professional experience has so far been concerned more with CR than with MR. The naïve realism (NR) dimension is mostly about physical realities that are the object of scientific fields outside my domain of expertise, and which I casually contemplate.

* A paradigm is, for us, a conceptual system that governs explicitly a person's conscious experience in a given situation as follows (Halloun, 2004a):

1. It determines the conditions that trigger every voluntary activity in the experience.
2. It sets forth standards, rules and guidelines for choosing and processing all that is necessary for the reification and continuous evaluation of the activity. This includes selection and analysis of empirical data when the experience is with physical realities.
3. It provides necessary conceptions, conceptual tools and methodology for conducting the activity and for refining the paradigm subsequently.
4. It supplies appropriate mnemonics for consciously retrieving necessary means and method from memory.

While the profile of a scientist is dominated, to variable degrees, by CR and MR, the profile of an ordinary person often consists of an unbalanced and incoherent mix of paradigms governed by the sort of *naïve* realism* (NR) that dominated the pre-Galilean era of science (mostly related to Aristotelian and medieval paradigms discussed below) or by some sort of classical realism (CR), yet it hardly touches on modern scientific realism. Still, no scientific dimension, including the classical one, can be as developed with an ordinary person as it is with a scientist. We refer to a non-scientific paradigm or paradigmatic profile: (a) as *naïve* paradigm or profile, when either is dominated by NR, and (b) as *common sense* (CS) paradigm or profile, when there is some balance between NR and CR (Fig. 1). A person with a naïve paradigmatic profile is called *naïve realist*.

The incommensurability between scientists' and students' paradigmatic profiles is due, at least in part, to the incongruence between the two groups' criteria for establishing the viability of knowledge. Scientists rely primarily upon empirical evidence whose reliability is determined by well-established norms pertaining primarily to the predictability of events in the real world. In contrast, students, like most ordinary people, often tend to "believe" in things at face value. Thus, the naïve realism (NR) dimension of a student paradigmatic profile often consists of two parts. The first NR part corresponds to situations where the expressed naïve ideas may be locally coherent in the sense that they may allow apparently consistent inferences in closely related domains. These ideas may be considered as viable (with trepidation) when confined to these domains (Reif & Larkin, 1991). Some of the viable ideas might still be at the level of uncorroborated beliefs, while others could have already been corroborated in some respects, though insufficiently, in the student personal experience. The second NR part corresponds to situations where naïve realism could not apply under any circumstance, and where CR (or MR) could be more appropriate from a scientist perspective. Like the first part, this one includes uncorroborated beliefs, as well as other ideas that appear to be duly corroborated in the student mind but whose claimed evidence is actually unreliable or not conforming to accepted scientific theory. The NR dimension is thus incoherent, and it often leads to inconsistent inferences and contradictions. In contrast, the classical realism (CR) dimension of a student paradigmatic profile consists of ideas that are all relatively viable. They are viable in the sense that they are somewhat compatible with scientific knowledge. Some of these ideas may not have already been duly corroborated in the student experience, and in this respect they may not be any different from other student beliefs. Furthermore, the size of the CR dimension by correspondence to a given science course is evidently smaller for students than for scientists concerned with the content of the course, and the more remote the course is from everyday life, the smaller the CR dimension in student profile.

We should not be surprised by the fact that student paradigmatic profiles differ significantly from those of scientists, and that they are by far not as systematically, reliably or coherently articulated as their scientific counterparts. Students are not afforded in their everyday life, or even at school, the sort of physical environment or the kind of social interaction that scientists are afforded in their observatories, research facilities and professional organizations. In this respect, scientists and students live in different worlds, and the two groups are driven by two different cultures (Cobern, 1995) of different goals, commitments, concerns and requirements (Reif & Larkin, 1991). The mismatch between student and scientist paradigms takes in many respects the form of a "clash of cultures". For many students, and especially naïve realists, science looks like a foreign culture that is being forced on them and that can only be met with resistance (Cobern, 1995). At best, students resign themselves to the authority of teacher and textbook and learn things by rote only to satisfy curriculum requirements. They often end up with a state of *cognitive dissonance* between what they learn in science courses and the way they interact with physical realities of everyday life, a way that remains mostly driven by

* A good proportion of naïve realists hold, in many respects, a positivist perspective on physical realities, and believe mistakenly that modern science does the same. They believe that salient features of physical realities are exposed directly to our senses and that human knowledge, including scientific knowledge, mirrors the apparent world. Many of them believe, like Mach, that scientists do not admit the existence of any physical reality unless they can perceive it directly with their bare senses or with some instruments ("esse est percipi"). Naïve realists also maintain that one should, and can, observe physical realities without any influence of prior knowledge, and this in order to guarantee the objectivity of constructed knowledge. In this respect, they believe that scientists collect and analyze empirical data in an inductive Baconian approach, without any à priori hypotheses or any à priori judgment regarding primary (salient) and secondary (inconsequential) details on which they need to concentrate (Halloun, 2004a).

naïve realism. The dissonance is often so deep that no educational theory or schooling system can ever entirely close the gap between naïve realism and its scientific counterparts. Subsequently, no formal education should consider a radical paradigmatic evolution (or paradigmatic shift in the Kuhnian sense) whereby secondary school or even college students may be expected to transform their common sense or naïve paradigms entirely into scientific paradigms. A more reasonable objective is to *transform naïve and common sense paradigmatic profiles*, and not paradigms, into more viable profiles whereby the naïve dimensions (NR in Figure 1) would be significantly reduced in favor of scientific dimensions (mainly CR in this figure). For meaningful and efficient success, such a transformation may proceed in many respects by recapitulating critical turning points in the history science, especially the one initiated by Galileo.

Students' naïve paradigms are particularly reminiscent of two major paradigms that dominated the pre-Galilean era and that we call, for convenience purposes, the Aristotelian paradigm and the medieval paradigm (Fig. 2). Both paradigms were underlined by a positivist philosophy that may possibly be characterized as the most natural philosophy for an ordinary person of any time, including our modern time. The Aristotelian paradigm started with Aristotle in the fourth century B.C. and dominated ancient philosophy in the western world for about sixteen centuries. Aristotle and his followers insisted that the reality of things is exposed directly to our senses, and that natural philosophy (science, in modern day's terms) should concentrate on explaining physical realities (systems and phenomena) without having recourse to the abstract tools of mathematics because, according to Aristotle, the abstract cannot explain the concrete. Furthermore, explanation of physical realities was about the predominant obsession of Aristotelians who: (a) did not see any point in

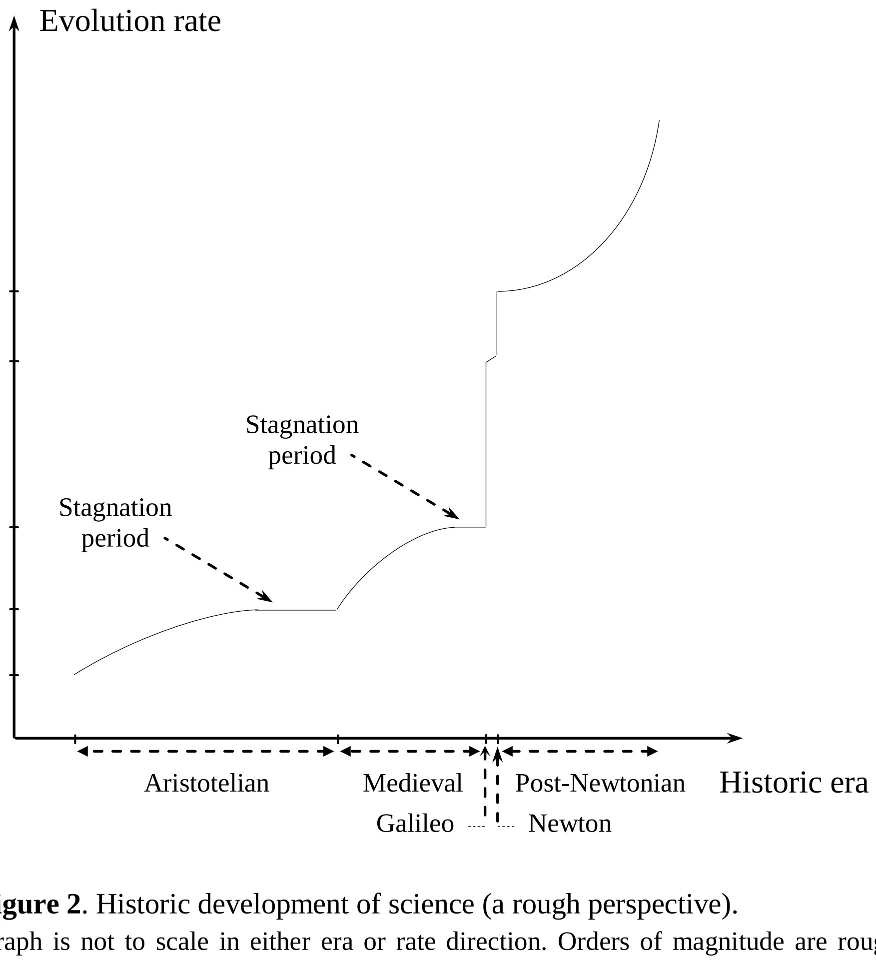


Figure 2. Historic development of science (a rough perspective).

Graph is not to scale in either era or rate direction. Orders of magnitude are roughly ordinal and not proportional. Natural philosophy (science) evolved at a slower pace and with less productivity in the Aristotelian era than in the medieval era. Both eras were dominated more by naïve realism than modern day scientific realism, thus ending in a stagnation or crisis period that induced a paradigmatic shift. The shift was far more radical with Galileo than with any of his predecessors, and it laid the foundations of modern day scientific realism.

distinguishing the descriptive function of science from its explanatory function, and who (b) insisted that there are always some requirements for any physical reality to exist and continue to be until it comes to its natural end. Among these requirements are convenient media (nature abhors vacuum) and particular causes (to maintain or change any state in which the reality might be). These requirements remain until the reality reaches its natural "goal", an end point determined by some intrinsic drive or tendency, or by some external power. The Aristotelian paradigm came under fire beginning in the sixth century A.D., and especially in the tenth and eleventh centuries. However, it managed to survive up through the thirteenth century A.D., despite the fact that it went through a long stagnation period whereby it failed to answer some questions to the satisfaction of philosophers (scientists) at the time (Fig. 2). Foundations of the Aristotelian paradigm began to seriously tumble down in the thirteenth century. The role of mathematics was by then recognized in natural philosophy, along with the necessity to describe physical realities more rigorously and vigorously. Some of Aristotle requirements for the existence and evolution of physical realities were abolished, and others were replaced with what appeared then to be more viable substitutes. For example, medium was no longer required for a number of phenomena to take place (e.g., free fall), and the notion of "Impetus" replaced Aristotle's natural "goal" and intrinsic drive. Impetus was conceived as an internal power or memory that physical objects develop while behaving under the influence of external agents so that they maintain their behavior once they are no longer under the influence of such agents. Like the Aristotelian paradigm, the medieval paradigm, mostly dominated by the tenets of the Impetus theory, reached a stagnation period around the turn of the fifteenth century (Fig. 2). This came about in part because of the continued positivist philosophy at the foundation of the medieval paradigm, its dependence on abstract, metaphysical rather than experimental or experiential dialectics, its obsession with a search for a cause for the existence and subsistence of every reality, and its unsystematic and inefficient use of mathematics.

Galileo is perhaps the most prominent figure at the turning point between ancient and modern science in the western world (Fig. 2), and his work can guide educators, as it did us, in the transformation of students' paradigmatic profiles. Galileo began his quest about physical realities in the late sixteenth century within the framework of the Impetus-dominated paradigm. He soon reached a dead end that led him to reconsider the very foundations of that paradigm. He came to the conviction that for natural philosophy (science) to provide viable answers about the physical universe, it has to follow somewhat counterintuitive paths characterized among others by the following:

1. In order to get to the reality of things, one should go *beyond direct perception* and asks oneself how *the world could* possibly exist in ways that are not exposed directly to our senses. According to Galileo, one often cannot directly perceive *primary* aspects of physical realities, i.e., salient aspects on which scientists need to concentrate in order to come up with *reliable* knowledge about such realities. *Secondary* aspects, i.e., irrelevant ones, dominate direct perception in a deceiving way. For example, if we were to rely on the appearance of things, we would have never given up the Ptolemaic perspective on the motion of the sun in favor of the Copernican perspective. We would have thus continued to mistakenly believe that the sun turns around the earth and not the other way around.

2. Primary aspects of the universe are "written in the language of mathematics". Without mathematics "it is humanly impossible to understand a single word of…this grand book, the universe", and one would "wander in a dark labyrinth", Galileo wrote in 1623 (Drake, 1974). For objective and viable knowledge of the universe, and in order to impose order on the apparent chaos of physical realities, one needs to superpose the rational world of mathematics on the empirical world. This superposition, as we shall see below, is primarily governed by mathematical modeling.

3. Description and explanation of physical realities are two primary objectives of science, and they need to be distinguished from each other. One should not confuse questions on *how* things exist or behave with questions on *why* they exist or behave one way or another. For efficient inquiry, description of physical realities may be undertaken separately from their explanation, and the former should precede the latter. In fact, Galileo concentrated the best part of his life on exclusively describing physical realities irrespective of, and even ignoring, possible causes behind

their existence and evolution. Later, Newton showed us how we may rationally infer causes of some events from the description of such events (particularly how to infer forces from the description of motion).

4. Scientific theory and inquiry should be model-based. In line with the first two tenets above, Galileo showed how one should, at a certain point, step out of the empirical world of physical realities into the rational world of conceptual models, and inquire about the empirical world indirectly through the rational world. Galileo's mode of inquiry is a back and forth cycle of model *construction*, *analysis* and *corroboration*. It may be extrapolated and summed up in the following five steps (Fig. 3): (a) in the framework of a convenient scientific theory, identify a particular *pattern* in the structure or behavior of a number of physical systems, (b) imagine an idealized world made up of a select set of primary features attributed to the pattern and build a conceptual *model* that reliably represents the pattern with only these features, (c) run the model, *analyze* it and infer appropriate laws and other theoretical statements pertaining to the idealized pattern, (d) examine to what extent the model allows reliable *predictions* about the physical pattern, and (e) refine the model and/or the theory if necessary, and/or reinforce the conceptual model and integrate it in the chosen theory.

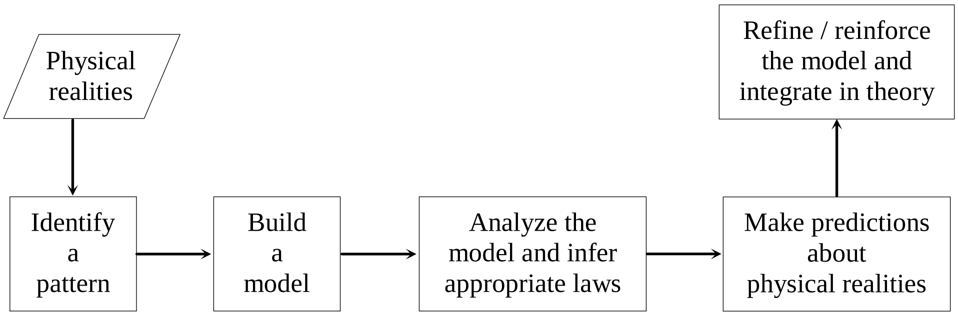
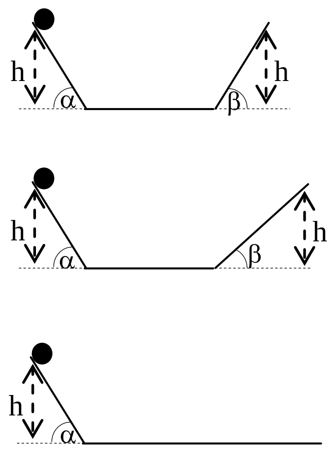


Figure 3a. Galilean modeling cycle.

This is a back and forth cycle of model construction, analysis and corroboration, governed by a conveniently chosen scientific theory. Evaluation (not shown in the diagram) continuously takes place throughout the cycle. One may subsequently go back, at any point, to a previous step and refine the process, especially to establish a better correspondence between the model and the real world and a better coherence within the chosen theory.

A particle glides on a frictionless track having the shape shown in the accompanying figure. The left ramp of the track has a fixed slope of angle α, while the right ramp can be tilted to any slope angle β. Because of energy conservation, when released from a point located at a height h on the left side, the particle reaches the same height h on the right side, irrespective of the value of the angle β. The smaller β is, the longer the distance traveled by the particle on the right ramp to reach the same height h. When β is zero, the particle travels an infinite distance to reach height h. In other words, once it hits the bottom of the left ramp, the particle will be subject to no net force, and it will keep gliding indefinitely at constant speed, and in a straight line*, on the now horizontal part of the track.



* Galileo had actually thought of a curved path around the earth.

Figure 3b. Galileo's analysis, through thought experiment, of a particle model leading to the principle of inertia in classical mechanics. The model represents physical objects in translational motion in an idealized, frictionless world.

Figure 3. Galilean mode of inquiry.

Newton took advantage of Kepler's work on planetary motion and extrapolated Galileo's kinematics, i.e., his *descriptive* models of the translational motion of physical objects. As a consequence, Newton came up with his famous laws of dynamics that *explain* the translation of celestial and, subsequently, terrestrial objects. Galileo and Newton, and more so the former than the latter, stand at the turning point between ancient and modern science. Thanks especially to Galileo's modeling perspective, science has witnessed a major leap in its history, a leap that set it on a new exponential course (Fig. 2). The way was thus wide open for increasingly new questions to be asked about the physical world, and for more and more reliable and sustainable answers to be found through model-laden inquiry.

Galileo's modeling perspective may be as much a critical turning point in the evolution of our students' paradigmatic profiles as it was in the history of science. Students' profiles and their evolution, up through college, recapitulate in many respects the left side of Figure 2 pertaining to Aristotelian and medieval paradigms. Unless they go through the sort of Galilean leap shown in this figure, it would be hard, if not impossible, for our students to transcend their naïve realism in the direction of modern day's scientific realism. One though should not expect such transcendence to be complete, not even through college. Eliminating naïve realism altogether from any person's paradigmatic profile would be a far-fetched target for many reasons discussed elsewhere (Halloun, 2004a). As suggested by Bachelard (1940) and Mortimer (1995), educators should instead concentrate on: (a) making individual students realize the limitations of the naïve part of their profiles, and thus (b) the necessity to build up viable counterparts in the scientific direction. We call, in modeling theory, for an evolution of students' paradigmatic profiles along these lines, an evolution that significantly reduces the naïve realism dimension and that builds up the classical and modern scientific realism dimensions to *realistic levels*. These levels, as we shall see in the following sections, correspond to what we call *basic models* in any scientific theory discussed in typical science courses.

2. MIDDLE-OUT THEORY STRUCTURE

A science course in secondary school or college is often about a particular scientific theory. A scientific theory is primarily concerned with the *description* and *explanation* of physical *patterns* in the universe, patterns disclosed and exploited through model construction and deployment. As Harré (1970, p. 35) argues, scientific "theories are seen as solutions to a peculiar style of problem: namely, 'Why is it that the patterns of phenomena are the way they are?' A theory answers this question by supplying an account of the constitution and behavior of those things whose interactions with each other are responsible for the manifested patterns of behavior [and constitution]". The dominance of patterns in the universe does not exclude the existence of irregularities (or anomalies), and it does not preclude scientists' interest in such irregularities. To the contrary, irregularities are captivating to scientists. They incite them to go deeper in their investigation, and, as a result, some apparent irregularities may turn out to be disguised instances of known patterns, while others do not. The latter often lead to new discoveries, and more specifically to new patterns. The search for patterns is now getting to the heart of every scientific discipline, even those disciplines, like ecology, that are primarily interested with irregularities and weak trends, and for which the search for patterns and universal laws has always been "a touchy subject" (Harte, 2002). Helping students develop systematic ways for identifying, exploring and reifying patterns in the real world must thus be at the core of science education. This may be achieved through model construction and deployment.

A *scientific theory* consists, for us, of: (a) a set of models or families of models, and (b) a set of generic rules and theoretical statements (axioms, laws, etc.) that are particular to the theory in question and that govern model construction and deployment and relate models to one another and to specific patterns in the real world. A given *scientific model is a representation of a specific pattern* in the real world. The pattern may be about the structure or the behavior of a number of physical systems, systems spread out throughout space and time in the universe. The model is a conceptual system mapped onto the physical pattern in the manner described in the following section of this paper. Mapping is done so that the model just captures the essence of the pattern, i.e., so that it represents only *primary* features that are salient to the model *function*, and not all details in the systems that manifest the pattern. The model may serve to: (a) *explore* the pattern, i. e., to describe, explain, and predict (or postdict) aspects of physical realities that are responsible for the pattern in question, and, eventually to (b) *reify* the pattern through the control or change of existing realities, or through the design and invention of new realities (like in technology).

Models are at the center of what we call *middle-out* structure of scientific theory. Many cognitive scientists have shown that, in accordance with the theory of prototypes and basic-level categories of Eleanor Rosch, “categories are not merely organized in a hierarchy from the most general to the most specific, but are also organized so that the categories that are cognitively basic are ‘in the middle’ of a general-to-specific hierarchy… Categories are not organized just in terms of simple taxonomic hierarchies. Instead, categories ‘in the middle’ of a hierarchy are the most basic, relative to a variety of psychological criteria” (Lakoff, 1987, pp. 13 and 56). For example, “dog” is “in the middle” of a hierarchy between “animal” and “retriever”, just as “chair” is between “furniture” and “rocker” (Fig. 4). Categories in the middle are *basic* in the sense that: (a) they ensure the best way possible a cohesive structure of human knowledge of any type, and that (b) they constitute the most accessible, efficient and reliable building blocks in knowledge construction and deployment. The middle-out hierarchy extends, from our point of view, from physical systems in the real world to conceptual

Categories Hierarchy (according to Eleanor Rosch & George Lakoff)		
SUPERORDINATE	Animal	Furniture
BASIC LEVEL	Dog	Chair
SUBORDINATE	Retriever	Rocker

Real World Structural Hierarchy:		
SUPERORDINATE	Matter	Galaxy
BASIC LEVEL	Atom	Solar System
SUBORDINATE	Elementary particle	Planet
Conceptual Hierarchy in a Scientific Theory:		
SUPERORDINATE	Theory	
BASIC LEVEL	Model	
SUBORDINATE	Concept	
Model Hierarchy:		
SUPERORDINATE	Emergent model	
BASIC LEVEL	Basic model	
SUBORDINATE	Subsidiary model	

Figure 4. Middle-out hierarchies.

* We define a *scientific paradigm* as a natural paradigm, i.e., a paradigm about physical realities that is shared by the members of a particular scientific community. A scientific paradigm has a well-defined scope in the real world. It serves specific functions regarding particular physical realities. To this end, it consists of (Halloun, 2004a):

1. Ontological tenets about physical realities.
2. A scientific theory, or a set of theories about such realities, along with epistemological: (a) tenets that underline the nature of various conceptions that make up any scientific theory, and that establish the correspondence of theory and conceptions to the real world, and (b) principles and rules for conceptual structure and categorization, and for theory organization.
3. Specific methodology (including standards, tools, rules, guidelines, processes) for: (a) theory construction, corroboration and deployment, and (b) continuous evaluation and refinement of all related conceptual structures and processes.
4. Axiological tenets some of which set the “value” of scientific theory and others govern scientist practice from an ethical point of view.

systems in the paradigmatic world as indicated in Figure 4. Scientific theories provide the "content" core of a scientific paradigm*, and models are 'in the middle' of conceptual hierarchy, between theory and concept.

The model-centered, middle-out structure of scientific theory ensures theory coherence and consistency from an epistemological perspective, and it facilitates people's development of scientific knowledge from a cognitive perspective. A scientific model is to theory and concept what an atom is to matter and elementary particles. Each elementary particle is essential in the structure of matter, but its importance cannot be conceived independently of its interaction with other particles inside an atom. It's the atom and not elementary particles that give us a coherent and meaningful picture of matter, and it's the atom that displays best the role of each elementary particle in matter structure. Now, Bohr's model of the atom is essential for understanding hydrogen-like atoms, and is often referred to as a "model" in physical science textbooks. However, the word model is seldom used in reference to other scientific models, which would give students the false impression that Bohr's model may be about the only scientific "model". Furthermore, various concepts and laws are often presented episodically, one after another in a given chapter, without relating them to one another in the context of appropriate models, whether implicitly or explicitly. Students are thus deprived of the opportunity to develop a coherent, model-based, picture of scientific theory, and they end up with a piecemeal, fragmented picture of the world. To get a feel of this picture, imagine what your knowledge about physical realities would look like should you've learned at school that matter consists of elementary particles and should no mention about the atom was ever made.

Models in a given scientific theory are, for us, also categorized in a middle-out hierarchy as shown at the bottom of Figure 4. In the middle of model hierarchy are basic models. A *basic model* is one that is simple enough to facilitate student learning of fundamental tenets and conceptions (concepts, laws, etc.) of the respective theory and of fundamental tools and skills of scientific inquiry. A basic model is yet generic enough to serve in the construction of more complex models in the

Free particle

Physical objects subject to no net force ($\Sigma \boldsymbol{F}_i = 0$), and thus maintaining constant velocity in any inertial reference system ($\boldsymbol{a} = 0$, $\boldsymbol{v}$ = constant).

Uniformly accelerated particle

Physical objects in linear or parabolic translation with constant acceleration ($\boldsymbol{a}$ constant) under a net constant force ($\Sigma \boldsymbol{F}_i$ = constant).

Bound particle in harmonic oscillation

Physical objects undergoing periodic back and forth translation (sinusoidal $\boldsymbol{a}$ function) under a net force that is proportional to their displacement from a center of force ($\Sigma \boldsymbol{F}_i \propto \Delta \boldsymbol{r}$). This model is often called simple harmonic oscillator.

Bound particle in uniform circular motion

Physical objects in uniform circular translation ($a = v^2/r$) under a net centripetal force ($\Sigma \boldsymbol{F}_i \propto \boldsymbol{r}/r^2$) of constant magnitude.

Particle under impulsive interaction

Physical objects whose linear momentum changes significantly, and almost instantaneously, like in the case of collision, under a variable net force ($\Sigma \boldsymbol{F}_i = \boldsymbol{f}(t)$) exerted for a very short period.

Figure 5. Basic particle models in Newtonian theory of classical mechanics, with an outline of the translational pattern that each model represents in inertial reference systems.

Particle models refer to physical objects the internal structure of which can be ignored when they are in *translation* without rotation or precession, in a specific reference system. Each *basic* particle model is made up of a single, dimensionless object: a particle.

theory. The set of basic models in Newtonian theory are given in Figure 5 for illustration. A student needs to understand the entire set of basic models so that s/he could meaningfully learn the theory in question, and realize a meaningful paradigmatic evolution.

At the subordinate level of model categories are subsidiary models. A *subsidiary model* is a simplified basic model, a particular case which students may usually be most familiar with, and that can serve as a stepping-stone for the comprehensive construction of the basic model in question. For example, the model of a particle in free fall (objects falling in vacuum in the absence of any force except for gravity) is a subsidiary model in Newtonian theory. It serves in the manner described in sections 5 and 6 of this paper for the progressive construction of the uniformly accelerated particle model (Fig. 5). At the superordinate level of model categories are emergent models. An *emergent model* is one that may be constructed by putting a given basic model together with one or more other models in order to represent a pattern that cannot be represented by either model separately. The model of a bound particle in uniformly accelerated circular motion is an example of emergent models. It emerges from combining two basic models in Newtonian theory shown in Figure 5, the uniformly accelerated particle model and the bound particle in uniform circular motion.

Some cognitive scientists, linguists and other researchers have argued that model-centered epistemology is not restricted to scientific paradigms, but that it extends to all sorts of human knowledge, and even to that of some animals (Johnson-Laird, 1983, p. 405 ff.). Bower and Morrow (1990) argue that "we build mental models that represent significant aspects of our physical and social world, and we manipulate elements of those models when we think, plan, and try to explain events of that world". Meanwhile, Johnson-Laird, Hestenes and others express a more radical position. According to Johnson-Laird (1983, p. 402), "*all* our knowledge of the world depends on our ability to construct models of it", and according to Hestenes (1995) "we come to know real objects (their properties and processes) *only* by constructing models to represent them in the mind" [italics added]. A more moderate position is expressed by Lakoff (1987) who argues that we "use cognitive models in trying to understand the world. In particular, we use them in theorizing about the world, in the construction of scientific theories as well as in theories of the sort we all make up" (p. 118). "The main thesis" of Lakoff "is that we organize our knowledge by means of structures called idealized cognitive models, or ICMs" (ibid, p. 68).

In an analysis of categorization data, Lakoff (1987) shows, and Giere (1994) supports, that human categorization is based on ICMs and not on similarity between individual features. ICMs govern the middle-out hierarchy across and within various categories. Along these lines, Giere (1994) argues that models of any scientific theory can be graded with some basic models in the middle. Basic models, according to Giere, are most important to develop the fundamental building blocks of a given scientific theory and corresponding rules of model construction and deployment. Our middle-out categorization of scientific theory and models (Fig. 4) and our focus on basic models (Fig. 5) resonate well with the positions of Lakoff and Giere.

3. MODELING SCHEMATA

The middle-out, model-centered structure of scientific theory is laid out explicitly in modeling instruction, i. e., while teaching science within the framework of our modeling theory. Students are guided to systematically develop the content of any scientific theory in the form of models of well-defined scope and structure, and to construct any conception (concept, law, etc.) only as part of, or for the sake of, a particular model or set of models. The content of a science course is thus rearranged to serve this purpose, and students are empowered with appropriate tools to meet this end. The most important of these tools are organizational tools that we call modeling schemata.

A *modeling schema* is an organizational template used to ensure that any conception, and especially a model, is built comprehensively, without missing any primary feature, and that it is integrated coherently in a given theory, all this in the most efficient, compact and coherent way possible. It also offers, directly or indirectly, well-defined rules for evaluating and employing the corresponding scientific conception. In a sense, modeling schemata are to meaningful learning of science what semantics and syntax are to mastering any language. A modeling schema sets the rules of correspondence of a conception to the real world just like semantics do with vocabulary. It also sets the guidelines for putting the conception together and relating it to other conceptions just like syntax in grammar. Two modeling schemata are especially helpful for teaching science. One is the model schema; the other is the concept schema.

The *model schema* is a four-dimensional template for putting together any scientific model (Halloun, 1996, 2001a, 2004a), at least those models that are the object of study in secondary school and college science. Two of the four dimensions, composition and structure, set the ontology and function of the model, and the other two, domain and organization, set its scope, all in terms of the scientific theory that the model belongs to, and by correspondence to physical realities displaying the modeled pattern.

The *domain* of a scientific model includes all physical realities manifesting the pattern that the model represents. These realities are called model *referents*. A model's domain can be delineated by answering questions of the sort:

- What physical systems does the model refer to in the real world?
- What pattern do these systems share in their structure and/or their behavior?
- Under what physical conditions?
- Under what limits of approximation and precision?

Model *composition* consists of concepts representing *primary* constituents and respective properties of physical systems, i.e., only those constituents and properties that are salient to the pattern. Concepts of interest to us at this level are mainly of two types: object-concepts and property-concepts. *Object-concepts* (or conceptual objects) represent physical bodies that significantly contribute to the making of the pattern represented by the model. These may be *objects* that enter in the make up of each physical system of interest, or *agents* in the environment of the system, i.e., physical bodies outside the system that interact significantly with objects inside. *Property-concepts* (or *descriptors*) represent primary physical properties of objects and agents, and of their mutual interaction. The composition of a model can be determined by answering questions like:

- What are the primary *objects* of a system and what object-concepts can represent them? (e.g., a particle in Newtonian mechanics; this is a dimensionless object, a point, that refers to physical objects whose translational motion is not affected by their geometric properties of shape and dimension).
- What are the primary *agents* in the respective environment and what object-concepts can represent them?
- In what kind of *reference system* can these objects and agents be most conveniently studied?
- What *intrinsic descriptors* (property concepts) characterize each object? (e.g., mass, charge).
- What *state descriptors* characterize each object? (e.g., position, momentum and other kinematical concepts).
- What *interaction descriptors* characterize object-object and/or object-agent interactions? (e.g., force, field and other dynamical concepts).
- What symbolic, pictorial, diagrammatic, graphical *representations* can most conveniently be used to depict all objects and descriptors above, and in what coordinate system?

Model composition is meant to discern between primary and secondary aspects of a pattern, i.e. between those aspects that need to be accounted for in the modeling process and those that may be ignored within the considered limits of precision and approximation. In model composition, primary object and property concepts are only listed and not related to one another. Model *structure* spells out relevant relationships among primary features of the pattern represented by the model. Model structure can be defined along four subdimensions, or facets, each dealing with a specific aspect of model referents in relation to pattern formation. These are the topology facet, the state facet, the interaction facet, and the cause-effect or causal facet. Each facet is distinguished conceptually by the nature of descriptors involved and the ways they are related in space and time. Various relationships are expressed in an appropriate reference system relative to which the pattern is conveniently identified. Such relationships come primarily in the form of laws that set the distinctive descriptive and/or explanatory *function* of the model. The structure of a model can be generated by answering questions like:

- What descriptive and/or explanatory function does the model serve? (e.g., a kinematical or a dynamical model in Newtonian Theory).
- What geometric structure does the model have? (e.g., none for a particle model made of a single particle, topography of many-particle models). This question sets the *topology* of the model.
- What *state* laws *describe* best the behavior of each object? (e.g., so-called kinematical equations of motion, like r(t)).
- What *interaction* laws quantify best the interaction of each object with other objects and agents? (e.g., Newton's law of universal gravitation, Hooke's law).
- What *causal* laws *explain* best the behavior of each object? (e.g., Newton's second law).
- What symbolic, pictorial, diagrammatic, graphical representations can be used to conveniently depict all the above?

Model *organization* situates a given model in the respective scientific theory. It establishes the relationship of the model in question to other models in the theory by answering questions of the sort:

- What are the limitations of the model?
- Where does the model fit in the middle-out model hierarchy (Fig. 4)?
- What features does it share with other models in the theory to which it belongs?
- How does it differ from other models?
- What other models complement it in the theory?
- Can it be merged with other models to form a new model that answers questions that cannot be answered with either model separately? If so, how?

Concepts are elementary building blocks of models. They gain their significance only when used in model construction, and more specifically in spelling out laws, definitions and other theoretical statements that make up the model structure. In order to build concepts comprehensively and integrate them coherently into respective models and theory, the model schema is complemented with the *concept schema*. This is a four-dimensional template used for the construction of individual concepts within the context of basic models (Halloun, 1998a, 2001a, 2004a). The four dimensions are scope, expression, organization and quantification. They are concisely presented below for property-concepts or descriptors.

A descriptor represents, to a certain degree and within certain limits, a particular physical property shared by many real world systems or phenomena. It has a domain confined to the represented property and a particular function (descriptive or explanatory) depending on the nature of the property. Domain and function constitute concept *scope*. A set of *correspondence rules* establishes viability conditions of the concept in the real world as well as its utility in the composition of models.

Each concept is expressed in science in a unique way associated with particular semantics that establish what the expression actually delineates in the real world or the rational world of scientific theory and paradigm. A mix of verbal, symbolic, iconic, and especially mathematical forms of *expression* is commonly used to communicate any scientific concept. The mix is necessary to come as close as possible to a comprehensive expression of the concept, since no single form can actually do so alone.

A descriptor gains its significance only after related to other descriptors within the contexts of models, and especially basic models. Concept *organization* sets criteria and guidelines for classifying a concept and for relating it to other concepts, all along with appropriate syntactic rules.

A descriptor cannot be scientific unless it is measurable according to well-defined *quantification* laws and rules. These set the sort of measurement which the descriptor can be subject to (nominal, ordinal, interval or ratio), and the means and procedures to which one can resort for determining values of the concept on a certain scale, and by comparison to a certain standard.

Modeling schemata are as much helpful for science teachers as for students. Teachers use them for planning and teaching lessons, and for assessing student learning and teaching practice. Under modeling instruction, the content of a teaching unit is usually organized around a specific model. Planning and teaching a lesson following modeling schemata ensure that students develop the model in question (or any necessary conception) without missing any salient feature. The same schemata can subsequently be used to develop an appropriate assessment taxonomy that covers all salient features of a particular model or other conception, and that helps logging the evolution of every student.

In the form presented above, modeling schemata are meant for immediate use more for teachers than for students. They serve as comprehensive templates or check-lists for planning, carrying out and evaluating instruction, and for putting more structure and coherence in the presentation of various models, laws and concepts in any scientific theory. Students need to systematically construct their conceptions following these schemata, but they need not, at least at the beginning of a course, to do so by going linearly and explicitly through each of the four dimensions of a given schema. In fact, a schema and its dimensions should not even be presented as such to students, at least not freshmen. As instruction progresses, teachers may encourage students to develop, for each schema, some sort of a flowchart or check-list for comprehensive model or concept development.

4. MODELING INQUIRY

The paradigmatic evolution promoted in modeling theory is about both content and processes, and the model-laden philosophy weaves throughout all aspects of the target evolution. Special attention is devoted to two modeling processes that we see as scientists' primary modes of inquiry about physical realities: (a) *construction* of a new model, corroboration included, in the context of particular real world situations in order to represent a given pattern in this world, and (b) *deployment* of an already constructed model for solving empirical or rational problems and for further knowledge development.

Students engage in the two modeling processes, model construction and model deployment, and develop necessary tools and rules, systematically and progressively through well-structured learning cycles described in § 6. Students are motivated to construct a new model on a need basis, mainly by letting them realize that whatever knowledge they have does not allow them to make reasonable predictions about particular empirical situations. They subsequently begin constructing the new model along its four schematic dimensions (domain, composition, structure and organization) progressively. They start with a crude subsidiary model, and they keep refining and expanding all schematic aspects of the model through appropriate deployment activities. These activities are chosen so as to convince students of the need to further develop (or refine) the model in specific directions. In this respect, model construction and model deployment are back-and-forth activities that complement one another in a modeling cycle (§ 6).

Most science courses are traditionally offered in a two-stage sequence of development and application of particular conceptions (concepts, laws and other theoretical statements). Conceptions are first theoretically developed in the main body of a given chapter, and *then* applied in end-of-chapter exercises. In such a sequential presentation, application exercises subserve conception development. In our approach, model deployment follows chronologically various stages of model construction, i.e., it takes place after a model is being formulated in one form or another. However, model deployment does *not* strictly follow *from* model construction and it does not subserve the latter. The two modeling processes complement one another with respect to helping students develop a scientific model as comprehensively as possible, and gradually evolve into the realm of science. Model construction is not a one-time shot, especially when it is done in accordance with the model schema. A model is constructed in a *spiral* approach whereby the empirical scope of a model (domain and function) and its rational weaving (composition and structure) are developed progressively in the context of empirical and rational situations of increasing complexity. Model construction goes through a series of inquiry activities in both the empirical world of physical realities and related data and the rational world of scientific theory and paradigm. As such, the process of model construction follows the same canons of engagement with the two worlds as model deployment. Nevertheless, model deployment offers learners a more flexible and effective platform than model construction to consolidate various modeling tools and rules, including those that govern insightful and regulatory negotiations within each of the rational and empirical worlds, and between the two worlds (§ 5).

In modeling instruction, students sometimes develop some prescriptive, generic schemes for modeling inquiry. Such *modeling schemes* emphasize the central role of models in all sorts of empirical or rational inquiry, including traditional problem solving for which the scheme of Figure 6 is devised. The strategy outlined in this figure starts by analyzing a problem givens (before identifying goals or reading questions) in order to choose, in an appropriate theory, the model(s) that can best represent the situation at hand. Once models are chosen, and only then, one can identify the problem goals in order to pick whatever is necessary for solving the problem from the model composition and structure, and then represent the chosen components mathematically in convenient, multiple ways (diagrams, equations, graphs, etc.). A mathematical model is thereby constructed, and is subsequently processed in order to reach a solution to the problem. Every step of the way is evaluated by correspondence to the empirical situation, and in terms of the chosen theory, in order to ensure the validity and viability of the step. The process ends with a paradigmatic synthesis that recapitulates all major lessons learned in solving the problem, along with their implications on deployed models. This may include possible refinement of models and respective theory. Modeling schemes like the one in Figure 6 are primarily meant to help students realize that the solution of any problem can be efficiently attained by identifying (or adducing) at first the appropriate model(s) for the situation. Once the model(s) are identified in a given problem, the answer to any question follows directly from model structure (provided that one has already developed such a structure following the model schema).

Model deployment activities are not limited to conventional end-of-chapter paper-and-pencil problems. They include, like in the case of model construction, observations in the real world, empirical experiments, thought experiments (à la Galileo), field projects, case studies, all chosen with a special attention to interdisciplinarity and designed to provide, every now and then, the opportunity for team work. Most importantly, deployment activities are not limited to the "application" of conceptual models in solving typical end-of-chapter problems. They involve a variety of *dialectics* within and between two worlds, the *empirical* world of physical realities and related data, and the

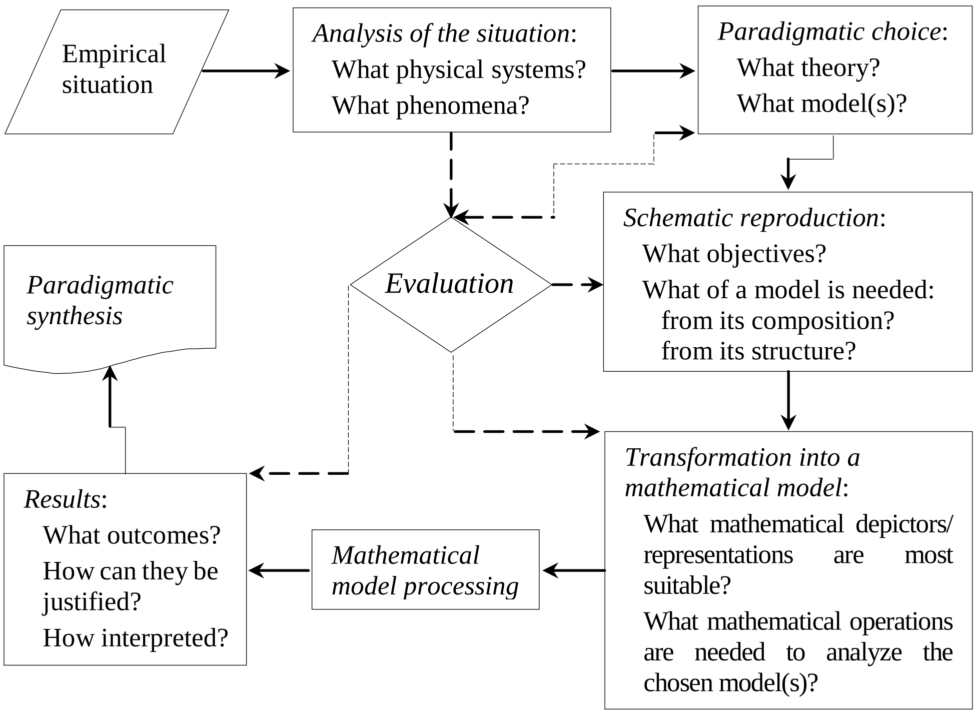


Figure 6. Model deployment in an application activity.

rational world of scientific theory. In other words, model deployment activities are not confined to the traditional exercises of exploratory inquiry (description, explanation, prediction of particular aspects of physical realities), exercises often limited to the application of specific theoretical statements to certain physical or fictitious realities. Instead, modeling activities are diversified so as to help individual students develop a balanced diversity of skills pertaining to both *exploratory* inquiry and *inventive* research (pattern reification through control or change of existing realities or through design and construction of new realities), while they meaningfully realize, and take advantage of, the potentials of every model in a given scientific theory. As such, modeling instruction maintains a balance between four categories of model deployment activities: application, analogy, reification, and extrapolation. As outlined in Table 1, each category involves a particular type of dialectics within the rational world or the empirical world, or between the two worlds, and targets particular aspects of exploratory and inventive research.

Throughout the processes of model construction and deployment, students develop necessary conceptions, tools and rules in accordance with a number of rules of engagement including the following:

1. All conceptions (from concepts to models) are developed, along with necessary tools and rules, and to the extent that is possible, in an experiential form. *Experiential knowledge* about a physical pattern is knowledge that one develops through interaction, or rather transaction in Dewey's sense, with empirical data about the pattern in question. This is in contrast with *traded knowledge* that one learns about, mostly at face value, from other people, from textbooks or any other medium of information dissemination.

2. Every conception, tool or rule is developed *on a need basis*. A new model is introduced, as we shall see in § 6, only after students realize the limitations of a previous model(s) and are confronted

Table 1
Taxonomy of model deployment activities (Halloun, 2004a)

Category	Dialectics	Inquiry	Objectives
Application	Empirical → Rational	Exploratory	Develop a rich repertoire of model referents Delimit model scope and set conditions of nomic isomorphism Develop rules of model adduction for pattern description, explanation and prediction or post-diction
Analogy	Empirical → Empirical	Exploratory Inventive	Develop rules for pattern identification Develop criteria for establishing analogy between model referents Apply these criteria for designing new referents
Reification	Rational → Empirical	Inventive	Develop rules of model-based deduction for pattern reification through: Control or modification of existing physical realities Invention of new physical realities
Extrapolation	Rational → Rational	Inventive	Articulate deduction rules to: Refine a model Develop new concepts or laws Construct a new model Predict the existence of unfamiliar referents or primary details of the modeled pattern

with a new pattern that cannot be represented by any model already developed. The same goes for subordinate conceptions (concepts, laws and other theoretical statements). Any such conception is introduced only when needed for the construction or deployment of a given model. No conception, tool or rule is ever introduced for its own sake, otherwise students would see no interest in developing it and they would fail to consolidate it with the rest of their knowledge. This would subsequently impede their understanding of the new notion as well as of the model(s) that make(s) use of it.

3. Every conception is developed *progressively* within the context of the model (or set of models) for which it is needed, especially when the conception is as involved as a law. For example, students progressively develop an understanding of the functional relationship expressed in Newton's second law before they come up with the corresponding formal statement of the law. They do so by exploring physical situations pertaining to the free particle model and others pertaining to the uniformly accelerated particle model so that they gradually develop the law from a nominal expression to its formal expression as shown in Figure 7. As such, students: (a) overcome the paradigmatic barrier set forth by the mistaken belief that a force is required for an object to change its position, and (b) meaningfully develop semantics and syntax associated with the functional relationship that the law expresses.

4. All tools (and conceptions) are developed along with associated *semantics and syntax*. No tool is used in modeling instruction under the assumption that students know how to use it, even when the tool is supposed to be fully developed in other courses. Semantic rules establish the correspondence between the tool being used on the one hand, and the empirical world and other representational tools, on the other. They set the norms for interpreting various elements of the tool or whatever product that the tool may bring about when used, both in the empirical and rational worlds. Syntactic rules spell out the conditions and guidelines for relating various elements of the tool to one another and to those of other tools, and for manipulating the tool in specific empirical and rational contexts.

5. No tool is ever localized or trivialized unless students discover that either is the case when the tool is put to the test under a variety of contexts. Students are encouraged to consider whatever tool used by scientists, irrespective of the discipline into which the tool was originally developed, or of the time at which its development took place. A tool commonly used in one scientific discipline may be considered for use in other disciplines. Some long forgotten tool may be reinstated; such tools are sometimes more efficient than ones that are nowadays being adopted and even revered.

1. *Nominal expression*: An object needs to interact with some agent(s) to change its velocity (in direction or magnitude), and not its position, in a given reference system. In the absence of any interaction, the object maintains a constant velocity in any inertial reference system.
2. *Ordinal expression*: When an object interacts with an agent that exerts a given force on the object, the velocity (or linear momentum) of the object changes in the direction of the force. The bigger the change of the object velocity in a given time (acceleration) for a particular mass of the object, or the bigger the mass of the object for a particular change in its velocity in a given time, the bigger the required force.
3. *Proportional expression*: Under the condition above, the required force is proportional to the object acceleration and mass.
4. *Formal expression*: Under the same condition, the required force vector **F** is equal to the product of the object acceleration vector **a** and mass m (**F** = m**a**).

Figure 7. Successive forms in which students progressively develop Newton's second law of dynamics.

5. MEDIATED LEARNING

Modeling instruction is student-centered, teacher-mediated. Individual students are afforded the chance to achieve the promoted paradigmatic evolution in an insightful and regulatory manner. Teachers *mediate* the process through structured learning cycles discussed in the following section. They provide guidance in timely manner so that students do not wander on their own in futile paths. They constantly induce students to reflect back on whatever knowledge that they might already possess and that relates to what they are learning in the classroom. Such reflection is rendered *insightful* in the sense that individual students become consciously aware of the limitations of their own conceptual structures or processes and of the sources of error when committed, and they explicitly realize what makes scientific realism superior to naïve realism from all perspectives. It is *regulatory* in the sense that individual students resolve any incommensurability between their own knowledge and scientific theory and paradigm, and they proceed through a paradigmatic evolution that meaningfully tames down the naïve dimension of student profile in favor of the scientific (classic or modern) dimension.

In conventional instruction, students are normally conditioned to verbally reproduce theoretical statements and heuristics in situations typical of, if not identical to, the ones discussed in class. The whole learning experience is primarily about *inscription of traded knowledge* in student mind, mostly in short-term memory, and seldom about formation of experiential knowledge. In the process, the student "learns about the real world from an intellectual distance, by reading about it", and is being filled "with information about the world, information that, in true written-word fashion, is removed from its context, at least to some extent, and represented rather than experienced directly" (Viau, 1994). Furthermore, students are seldom afforded the chance to go through a reflective experience whereby they could relate what they are told and shown in class to their own paradigms, and subsequently regulate, à la Dewey or à la Piaget, whatever "conflict" or dissonance that might emerge in the process. As a consequence, students usually memorize by rote various theoretical statements and related problem solving routines with the only interest of passing course exams rather than learning something that could be personally relevant and meaningful. Their naïve realism remains entrenched in their minds, and they keep resorting to this realism in their everyday life and not to what they learned in class, thus ending up with a state of cognitive dissonance as noted in § 1 above.

Modeling instruction reverses the situation through insightful and regulatory reflection that involves, among others, dialectics or "negotiation" modes shown in Figure 8. A student often needs to be engaged in all three negotiation modes across all dimensions of her/his paradigmatic profile (Fig. 1), but especially vis-à-vis the dimension or paradigm dominated by naïve realism. One of the three

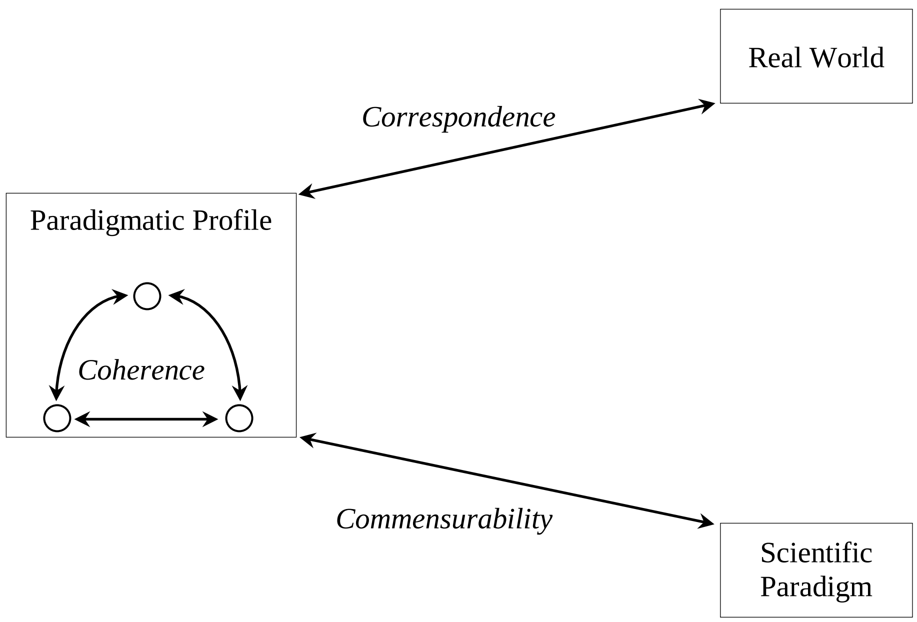


Figure 8. Rational-empirical dialectics for the evolution from the realm of naïve realism or common sense to the realm of science.

modes is an intrinsic rational negotiation, an assessment of *internal coherence* of a given naïve (or even common sense) paradigm. The other two are extrinsic negotiations. One involves an empirical assessment of *correspondence* of a student paradigm to physical realities. Another involves a rational assessment of *commensurability* between the student paradigm and the corresponding scientific paradigm. Depending on whether assessed paradigmatic components are originally viable (from a scientific perspective), naïve or missing, a negotiation of any type may result respectively in the reinforcement, modification or replacement of existing paradigmatic components, and/or the construction of new ones. The outcome, in other words, consists either of the possible *transformation* of existing viable or naïve knowledge or the *formation* of missing one (Halloun, 1998b, 2004a).

The outcome of a learning experience is determined primarily: (a) by the model being developed and corresponding epistemological and methodological requirements, and (b) by the initial state of students' paradigmatic profiles. It is then the teacher's responsibility to determine what sort of dialectics are most effective for those profiles to evolve and meaningfully incorporate the model of interest, and what sort of intervention or mediation is most appropriate to this end.

In an analysis of research published in the last two decades, Taconis, Fergusson-Hessler and Broekkamp (2001) found that teaching approaches that improve significantly student problem solving in science courses share the following three characteristics: (a) the deliberate intention "to enhance the quality of [students'] knowledge base", with a special "attention for schema construction", (b) "the availability of external guidelines and criteria…, i.e. objective [guidelines and criteria] provided by experimental set up or the teacher", and (c) "the presence of immediate feedback". The authors also found that "letting students work in small groups does not improve problem-solving education unless the group work is combined" with all three features just mentioned. Our modeling approach (Halloun, 1996; Halloun & Hestenes, 1987) came on top of the list of best practices identified by the authors. Taconis et al. (2001) had also noted that "a considerable part of the teaching experiments over the past 10 years has been devoted to aspects of learning tasks that are not effective, such as group work without immediate feedback or external guidelines and criteria", and that "treatments focused on the knowledge base have been given comparatively little interest". Many educators have come lately to recognize the shortcomings of modern educational trends that emphasize student-centered environments that are relatively free from all sorts of structuring. Even some constructivists have come lately to realize the need "to structure the environment in ways that would lead to a deeper understanding of science" and to recognize teachers' pivotal role in the process by admitting that "until each student respects the teacher and is willing to construct that person as his/her teacher, there is little point in proceeding with a curriculum that provides students with autonomy and opportunities to learn through inquiry" (Seiler, Tobin & Sokolic, 2001).

Modeling instruction is *student-centered* in the sense that it engages individual students actively in the learning process, but it does not leave them out entirely on their own free will. It has a specific agenda to fulfill: meaningful and insightful paradigmatic evolution within the confinements of a given curriculum. This agenda cannot be fulfilled without teacher mediation. In fact, there is no meaningful learning without teaching, at least not for the overwhelming majority of students who cannot get self-educated. "We have centuries of evidence to show that natural thinking is neither rational nor scientific. Scientific thinking has to be cultivated and nurtured. It is the result of education… Without teachers there are neither scientists nor scientifically literate citizens" (Matthews, 2000, pp. 332, 349). Research has shown that even "gifted" or "genius" experts who out-perform their peers in arts and science owe their achievement to the fact that they benefit from "sustained and specialized intervention from skilled teachers and parents" and especially "master teachers who either themselves had reached that level or had previously trained other individuals to that level" (Ericsson & Charness, 1994). Teacher intervention is advocated, in modeling theory, often not in the form of conventional lecture and demonstration, but in a sort of "mediated learning experience" whereby the teacher "mediates, transforms, reorders, organizes, groups, and frames" appropriate learning activities (Feuerstein & Jensen, 1980).

In modeling instruction, teacher mediation preserves a central role for student engagement and active participation in decision-making. Depending on the circumstance, mediation may take the form of moderation, arbitration, negotiation or initiation, and it always involves *teacher feedback*. The level and extent of this feedback increase progressively from moderation to initiationin a way to prevent students from going astray and to keep their reflective inquiry aligned as closely as possible with scientific inquiry. Moderation and arbitration are appropriate when students have their own ideas about topics of instruction, and when they can regulate these ideas almost on their own, given appropriate guidance. Otherwise, and depending on the intricacy of the situation, negotiation or initiation become more appropriate (Fig. 9).

As *moderator*, the teacher solicits ideas about a particular topic, and then guides students to compare ideas and resolve possible incompatibilities to the extent that they can do it on their own. The teacher does not intervene directly in the process to resolve the matter in favor of one idea or another. S/he can only passively supply some rational or historical details, or some empirical data that may help students brainstorm, clarify to one another specific ideas of their own, or bypass a stalemate which they may get to. The teacher gets more involved in the mediation process as an *arbitrator*. This role is especially important when students have conceptions or follow rules of engagement that are incommensurate with science (naïve, or of limited viability). The teacher would then bring concerned students first to a conscious state of *cognitive disequilibrium*, and direct them afterwards to negotiate things with their colleagues so as to get them resolved in favor of a particular position that is viable from a scientific perspective. The teacher does so first by invoking among students a sort of Socratic dialogues (Hake, 1987, 1992) that fosters rational-empirical dialectics for coherence and correspondence assessment of student ideas (Fig. 8). When this fails to bring things to a satisfactory closure in due time, the teacher shifts to scaffolding (negotiation or initiation) and offers the scientific position as an alternative that students are asked to ascertain.

Students: Provide viable ideas Compare ideas and try to work out incompatibilities, mainly through coherence and correspondence assessment	⟷	Moderator: Solicits ideas (conception(s)/ process(es)) Helps students clarify their ideas Calls not openly for regulation
Students: Provide ideas, some viable and others not Compare and regulate ideas, mainly through coherence and correspondence assessment	⟷	Arbitrator: Brings students to a state of cognitive disequilibrium Guides them through regulation
Students: Provide non-viable ideas Come to a deadlock Compare own ideas to scientific alternative (commensurability assessment) and regulate	⟷	Negotiator: Helps students realize the shortcomings of their own ideas Proposes scientific alternative for consideration
Students: Have no related ideas Infer required idea(s) or ascertain it as offered by the teacher	⟷	Initiator: Helps students realize the need for new scientific idea(s) Provides instructions to infer ideas or offers them for consideration

Figure 9. Modes of mediated learning.

Each form of student engagement (boxes on the left-hand side) is mediated by a particular form of teacher intervention (opposite boxes on the right-hand side). Note a decrease in student autonomy and an increase in teacher authority as the teacher role evolves progressively from moderator to initiator.

Scaffolding is, for us, the type of mediation whereby the teacher gets most involved in directing the learning experience in the scientific direction. This sort of mediation is resorted to when moderation and arbitration fail to bring about students' self-regulation. It takes the form of *negotiation* when students already possess non-viable ideas about the topic of instruction, and of *initiation* when this topic is so unfamiliar to the students that they practically possess no related ideas. In both cases, and like in the case of moderation and arbitration, the teacher begins her/his mediation by confronting students with empirical situations or data. As *negotiator*, s/he asks students to put their own ideas to the test (e.g., by making certain predictions) in the context of these situations in order to bring them to a state of cognitive disequilibrium. When students fail to regulate their own ideas, the teacher confronts them with the scientific alternative and guides them through a process of commensurability assessment (Fig. 8). The scientific position is though not imposed in an authoritative way, but it is offered only as an alternative that students are asked to consider and ascertain on their own in order to be convinced of its viability. As *initiator*, the teacher first helps students realize that they cannot treat the empirical situations at hand with the knowledge they already possess, and that they need to develop a new model or new conception(s) to this end. S/he then guides them to infer the appropriate conception(s), and/or to rationally derive such conceptions from prior knowledge. The teacher may provide students with appropriate tools in the process. When students fail to construct the target conception, or conduct a particular modeling process, the teacher induces them to do so in a more direct way by presenting them with the scientific conception or process in the manner followed in the case of negotiation. In both scaffolding cases, and following regulation of student knowledge state, students would be asked to deploy the newly developed knowledge in a sequence of modeling activities where the teacher can gradually retreat from direct intervention, somewhat in the manner promoted in cognitive apprenticeship and similar modes of instruction (Heller, Foster & Heller, 1997; Shore et al., 1992; Roychoudhury & Roth, 1996). Scaffolding is especially needed at the beginning of a science course when students develop the most fundamental basic models (e.g., free particle and uniformly accelerated particle models in Newtonian theory). Subsequently, the teacher progressively moves away from this mediation form as students become more and more autonomous in model construction and deployment. The nature and the course of teacher mediation are in fact primarily governed by the stage at which students are in a given learning cycle (§ 6).

A trade-off exists between student autonomy and teacher authority in mediated learning (Fig. 9). Teacher feedback gradually increases as mediation shifts from moderation to arbitration, and then to negotiation or initiation. Lecturing, in the traditional sense, may sometimes be required, especially in the case of scaffolding. The more students are incapable of regulating their knowledge on their own, the more authority the teacher needs to assume, and the less autonomy students can be afforded, in order to ensure that the target paradigmatic evolution takes place efficiently and within the practical constraints of the course. Teachers can anticipate the type of mediation and level of feedback when they are aware ahead of time of the kind of conceptions students possess about the topic of instruction. To this end, they need to be equipped with a battery of diagnostic instruments that would help them identify and categorize student preinstructional knowledge state, and decide subsequently for the appropriate mediation strategy (Halloun, 2003).

6. LEARNING CYCLES

In modeling instruction, the content of a science course is subdivided into units, each devoted to the development of a particular model. Students complete a unit through a teacher-mediated, well-structured learning cycle. The idea of a learning cycle as a *structured, mediated* form of learning was first put forth by Karplus (1977), primarily for teaching concepts of elementary school science within the framework of Piaget's theory of intellectual development. Karplus "learning cycle consists of three instructional phases that combine experience with social transmission and encourage self-regulation… These three phases are exploration, concept introduction, and concept application". In the first phase, students are invited to explore an unfamiliar empirical situation in ways that "raise questions or complexities that they cannot resolve with their accustomed patterns of reasoning… As a result, mental disequilibrium will occur and the students will be ready for self-regulation". The teacher introduces a new concept or principle in the second phase to resolve the problem at hand, and then students apply it in the third phase where "familiarization takes place as students apply the new concept and/or reasoning pattern to additional situations". Social transmission (i.e., teacher lecture for transfer of traded knowledge) is reduced in the first stage. It reaches its peak in the second phase where teachers reclaim their conventional role of lecture and demonstration, and it winds down in the third phase where "physical experience with materials and social interactions with teacher and peers play a role" (Karplus, 1977).

A learning cycle is, for us, a modeling cycle, a cycle for model construction and deployment. It is a student-centered, teacher-mediated cycle designed explicitly to foster the paradigmatic evolution we aim at in the most effective and efficient way possible. It draws on Karplus and related works of merits in science education. Our typical modeling learning cycle (MLC) is a five-phase cycle. Phases are, in order, exploration, model adduction, model formulation, model deployment, and paradigmatic synthesis. Each of the first four phases goes in two stages (Fig. 10). A modeling cycle as presented below represents the ideal cycle that students may be guided through. Relative adherence to the cycle depends primarily on students' initial knowledge state, the complexity of the model under construction, and practical classroom constraints. Only experience can tell a teacher to what extent s/he needs to follow the cycle.

A modeling learning cycle begins with the *exploration* phase. This is a two-stage phase devoted to motivate students to construct a new model of well-defined scope and to let them subsequently propose, in a crude form, a number of candidate models. In the first stage, called *monstration* stage (MLC1 in Fig. 10), a number of empirical situations sharing a given *pattern* are exposed so as to bring students to a state of *cognitive disequilibrium*. More specifically, students are brought to realize: (a) that the pattern at hand is outside the scope of prior knowledge (already constructed models, if any), i.e., that such knowledge is inadequate for describing, explaining and/or predicting the pattern in some respects, and thus (b) that a new model is needed in order to come up with the correct inferences about the pattern under investigation. Construction of the target model begins in the second stage of the cycle, the stage of *nominal models proposition* (MLC2), with crude subsidiary models. Subsequently,

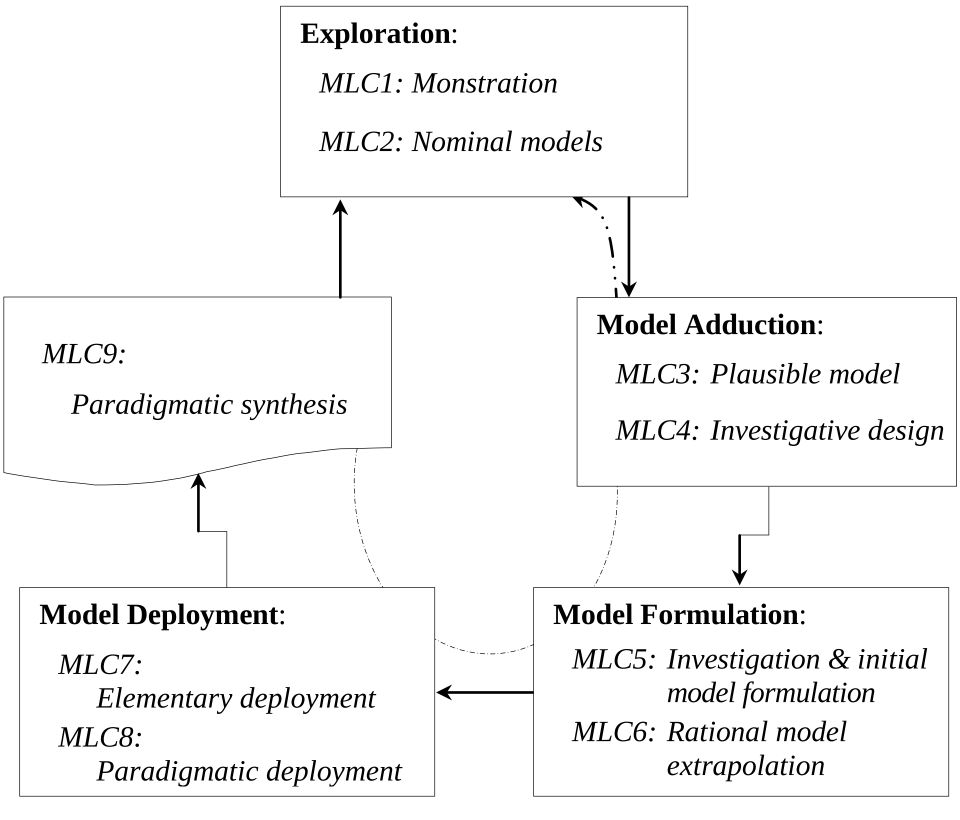


Figure 10. Modeling learning cycle.

The dashed, curved arrow indicates that one may go back to any preceding phase as a result of rational and empirical *evaluation* that takes place continuously throughout the cycle.

and throughout the cycle, students are brought closer and closer to the target scientific model through progressive refinement or approximations of the proposed models.

A model is *progressively* developed throughout a given cycle. When students possess alternative conceptions of limited viability, modeling activities begin with these conceptions and proceed to get them gradually refined until they become commensurate with scientific theory. In this respect, the construction of a given model may begin with one or more *subsidiary models* that correspond to the target model, and that students might be familiar with from everyday life and/or from other courses. Otherwise, students begin the process with the construction of a new subsidiary model. Various schematic dimensions of the subsidiary model are then gradually refined and built up until the model acquires the desired form. This is how, for example, construction of the uniformly accelerated particle model may begin with the subsidiary model of a particle in free-fall. At some levels, *successive refinements* of the subsidiary model, or of any student conception of limited viability, may follow the approach prescribed by Barbara White in her ThinkerTools. White (1993) developed a computer program whereby, among others, students develop the concept of constant force through a hierarchy of simulation activities, beginning with an activity that simulates the force with identical pulses imparted to a dot on a computer screen.

A *nominal model* constructed in the second exploration stage (MLC2) is a generalization of a subsidiary model. As noted above, a subsidiary model is originally mapped on a particular instance of a pattern, a particular system or phenomenon that students are familiar with, whereas the emerging nominal model is about the pattern itself, i.e., about all physical realities sharing the pattern. Both subsidiary and nominal models are entirely constructed by students, and the underlying student paradigms may be anywhere in the profile spectrum extending from naïve to scientific. The structure of the subsidiary model may be well developed in student minds. However, students are intentionally guided to generalize the particular structure of this model in a nominal form (Fig. 7) at this stage in order to ensure that peer negotiations and self-regulation in the coming stage proceed in the right direction, and to reduce the chances of coming back to refine model composition in subsequent stages.

Students negotiate subsidiary and nominal models among themselves under teacher moderation. As a moderator, the teacher brings students together to discuss their own models among themselves and practically refine them on their own (Fig. 9). S/he could intervene when students fail to do so, but with the only purpose of clearing the way of student negotiations from any noise. This may involve clarification of some student views to the rest of the class, reminding students of conceptions they ask about, passive supply of some empirical data, historical cases or any information that may help students brainstorm and bring their naïve ideas to the surface or get out of any possible gridlock in their negotiations. By the end of this stage, students eliminate all models that they duly consider to be non plausible, and they would be left with no more than three candidate (nominal) models for consideration in the coming stage.

The exploration phase is followed by the *model adduction* phase. This second MLC phase is intended to bring students to concentrate on a single plausible model that appears to be reliably mapped on the new pattern that is being investigated in the cycle. This is also a two-stage phase. The first stage (MLC3 in Fig. 10) is devoted to the proposition of a *plausible model*, and the second stage (MLC4), to the proposition of an appropriate *investigative design* for empirically testing this model. By the end of this phase, students resolve major incommensurability between their own models and the target scientific model while enhancing their methodology of inquiry. As a consequence, they significantly reduce the naïve dimension and build up the scientific dimension of the corresponding profile (Fig. 1).

In MLC3, students compare nominal models they proposed in the previous phase so that they reach a consensus on a single model. The emerging model is supposed to bear all viable elements of its predecessors. It is a hypothetical model that students conjecture explicitly according to the model schema. Nominal hypotheses conjectured in the exploration phase are gradually converted into ordinal hypotheses, and then, if possible, into ratio-type or proportional hypotheses (Fig. 7). The plausible model may still include some residual secondary (non salient) and/or naïve elements that students could not entirely resolve, residues shared by all or some groups of students. These residues will be cleared out in the next phase.

In MLC4, students propose and negotiate ideas leading to an investigation designed to assess the plausible model so that it becomes ready for refinement in the following phase. Depending on equipment availability and procedural feasibility, the design can pertain to a classroom or field experiment, to observations in the real world, or to empirical data about the pattern of study provided by teacher or any other reliable source.

The teacher whose role was restricted to moderation of student brainstorming and negotiation in the previous phase assumes now a more active role, an arbitration role. As an arbitrator, in MLC3 the teacher intentionally steers student interaction in the direction of a single candidate model that is proposed in accordance with the model schema and that has a relatively high degree of viability and low degree of naïveté by comparison to its subsidiary and nominal predecessors. If necessary, s/he also ensures that appropriate new conceptions be constructed to this end. In MLC4, the teacher makes certain that students come up with a sound investigative design to assess the tentative model along with necessary norms and criteria for model acceptance and refutation.

Efficacy and efficiency of a learning cycle depend mostly on the first two MLC phases, and especially on the model adduction phase. The more of their own ideas they expose in these two phases, and assess in class by comparison to one another, and the more transparent and focused the investigative design becomes in their minds, the better chance students stand to bring the self-regulation process to a meaningful conclusion at this point and progress in the direction of a truly scientific model. Gradual formulation of this model takes place for the most part in the third MLC phase, and is achieved in the last phase following model deployment.

The third phase of the modeling cycle is the *formulation* phase. This is also a two-stage phase devoted to the formulation of a comprehensive and scientifically sound model based on the outcomes of the investigative design of MLC4 that students carry out in this third phase. The formulation will though not be exhaustive because, by now, the model would not have been sufficiently deployed yet. Model deployment takes place in the fourth MLC phase. New insights will subsequently be gained into various aspects of the model, and the model will be brought then to a maturity level that is high enough to conclude the learning cycle.

In the first formulation stage (MLC5 in Fig. 10), students conduct, in collaborative groups, the investigation they designed in the previous stage, and refine the plausible model of MLC3 in light of the investigation outcomes. By the end of MLC5, students achieve a *preliminary formulation* of the target model, a viable but incomplete formulation. The model thus formulated is a refined, formalized form of the plausible model conjectured in MLC3. Hypotheses in the latter are corroborated, modified or replaced, and the originally conjectured relationships are more precisely expressed (e.g., ordinal or proportional hypotheses are turned into ratio-type law statements). Seldom new major elements which have not been thought about before in one form or another emerge in the newly refined model. There is virtually a one-on-one mapping between this model and its predecessor. It is thus common that some primary features of the target model may still be missing. Aside from issues that may be brought about only after model deployment, student investigations cannot possibly cover all model aspects at this stage. Furthermore, various constraints may make it impossible for students to empirically corroborate or even induce certain model aspects. Such aspects may then only be inferred by rational analysis and extrapolation, and perhaps only through teacher initiation (Fig. 9). These aspects make the object of the next stage.

In the second formulation stage (MLC6), the model constructed so far gets rationally analyzed and extrapolated so as to come close to a comprehensive model formulation. *Rational extrapolation* can take place within the model in question, and/or from previously constructed models. For instance, by the time they have achieved MLC5, students would have already refined, in the form of scientific laws, all hypotheses conjectured in MLC3. When these laws are insufficient to complete the model structure, students can be guided to induce missing laws from available data if possible. If not, they can be guided to formulate these laws by rational extrapolation of laws they have already formulated in MLC5, and/or laws formulated in previous learning cycles, be it generic laws or laws that are particular to some old models.

The teacher assumes consecutively two different roles in this third phase of the learning cycle. At the beginning of MLC5, and all through the actual investigation process, the teacher retracts from the arbitration role to supervise the process from a distance as a moderator. Once the investigation is completed and students have prepared their reports, the teacher gets again more involved as an arbitrator of students' interaction to ensure that the model is properly formulated in MLC6. Sometimes, the teacher may even find it necessary to step up her/his intervention to take the form of scaffolding. As such, the teacher may instruct students to follow explicitly a specific path and/or provide them with necessary concepts and tools that are totally missing from their paradigmatic profiles and that are indispensable to complete model composition and structure. Scaffolding may involve lecturing when practical constraints prevent students from coming up with any of these concepts and tools on their own.

A model gains its full significance only after deployed in the real world for describing, explaining, predicting and controlling the structure and/or behavior of a variety of existing physical realities, for inventing new conceptual or physical realities, and for subsequently bringing to new horizons the theory and paradigm which the model belongs to. New insights are gained as the model is deployed in different contexts and envisaged from different perspectives. It gradually gains in scope (domain and function), and it becomes better and better situated in the corresponding theory.

The model constructed up to the third phase of a modeling cycle is deployed in the fourth phase. *Model deployment* activities are chosen so as to allow students complete and reinforce all four schematic dimensions of a model (especially issues that may still be pending at this point), and promote model-based inference in various empirical and rational contexts. Activities are conducted following systematic schemes that students develop for adducing the appropriate model(s) to the "givens" in a situation, and not following rules of thumb or context-specific prescribed routines to determine convenient "relationship(s)" between givens and unknowns. Such schemes and required tools and skills are progressively developed in two deployment stages. In the first stage (MLC7), students deploy in each activity only parts of the model formulated in MLC6. Deployment situations get progressively more complicated until they reach the level of *paradigmatic situations* in MLC7 (Halloun, 1998b), situations each of which requires deployment of the model structure in virtually its integrity. Activities in both stages are chosen to cover all four deployment categories distinguished in Table 1 (application, analogy, reification, and extrapolation), and they are not limited to conventional paper-and-pencil exercises and problems. They include, in addition to conventional exploratory activities, investigative activities of all sorts, thought experiments, historical and contemporary case studies of interdisciplinary nature.

Deployment activities, and especially those of paradigmatic deployment, are conducted under teacher arbitration following the same guidelines of the previous two stages. Students are encouraged more in this stage than ever before to rely on themselves and collaborate with the members of their groups whenever possible, and to carry out every deployment activity while reflecting on their own knowledge and regulating it in the most insightful way possible. To this end, they conduct every deployment activity in the manner they conducted the investigation of MLC4 and MLC5, individually or in groups, during class hours whenever that is possible. They expose their work afterwards and discuss it in class the same way they did in MLC5. When peer negotiations head to a dead-end after all possible arbitration, and only then, the teacher may intervene to resolve the issue one way or another by scaffolding (Fig. 9).

A learning cycle and thus a modeling unit of instruction are not brought to closure with deployment activities. New insights are gained about the model under construction in the deployment phase. Students need then to consolidate their experience in this phase with what they achieved in previous phases. *Paradigmatic synthesis*, the last phase of the learning cycle (MLC9 in Fig. 10), is devoted to this end and to subsequent recapitulation of the paradigmatic evolution students gradually achieved in the cycle. The synthesis in question differs significantly from summaries typically offered at the end of a chapter in conventional textbooks. Paradigmatic synthesis is done by the students.

Consolidation and recapitulation are conducted as critically as any other process undertaken during the cycle. Every point is systematically evaluated in this stage like in any other stage, and this along the lines of Figure 8. If determined to be viable, students proceed to the following point. Otherwise, students go back to a previous stage where the source of the problem might be rooted so that they can reconsider things and refine them appropriately. The process continues under teacher arbitration until students complete the synthesis of the current cycle and set the stage for the following cycle. Such an evaluation is in fact not limited to this stage, but it is carried out throughout an entire cycle, as implied in the dashed, counterclockwise arrow of Figure 10.

7. Efficacy of Modeling Instruction

Development of modeling theory has gone in the last two decades with this author (and is still going) through cycles similar to the modeling cycle described above. The theory that has repeatedly shown to be efficacious for secondary school and college physics courses is now being progressively deployed in various scientific disciplines and at all educational levels. Early outcomes show that modeling theory is at least as promising in the latter respects as it is for physics education.

Normative evaluation of modeling theory is the object of a number of publications. A comprehensive overview of the evaluation process is presented in a recent paper (Halloun, 2003), and it shows the relative efficacy of various components of the theory in fostering the paradigmatic evolution advocated in this paper. All in all, when deployed in secondary school and college physics courses, the theory has been leading to the following outcomes:

Better conceptions. Students show significantly better conceptual understanding of scientific theory following modeling instruction than following other forms of instruction. The Inventories of Basic Conceptions (IBC) is a battery of standardized instruments developed by this author for assessing student qualitative, conceptual understanding of basic conceptions (concepts, laws) in given courses (Halloun, 2005). IBCs include instruments similar to what used to be called the Mechanics Diagnostic Test (Halloun, 1984; Halloun & Hestenes, 1985b) or the Force Concept Inventory (Hestenes, Wells & Swackhamer, 1992) in physics education. Under modeling instruction students score on IBC posttests up to two standard deviations, on average, higher than students who learn physics under conventional instruction of lecture and demonstration.

Better processes. When given identical assignments and exams consisting of tasks similar to end of chapter problems typically found in traditional textbooks, students score on average up to three times better under modeling instruction than under conventional instruction. The better performance of students following modeling courses is due to their systematic use of problem solving (modeling) procedures that are in line with Figure 6.

Better views about the nature of science. The Views About Science Survey or VASS (Halloun, 2001b, Halloun & Hestenes, 1998), is a battery of instruments designed to assess student views about the nature of scientific theory and inquiry. As assessed by VASS, students express views about the nature of science aligned with scientific realism rather than naïve realism, more so following modeling instruction than following other forms of instruction.

Better learning styles. VASS also includes parts designed to assess how students go about studying a given science course. It shows that students tend to follow the canons of reflective and insightful inquiry in their study, more systematically under modeling instruction than under other forms of instruction.

Lower attrition rates. The rate of students who withdraw from a given course before its end or fail the course upon its completion is in modeling courses down to one third of what it normally is in conventional courses.

Equitable learning. May be the most significant outcome of modeling instruction is that it bridges the gap in a way yet unmatched between students who are traditionally considered as low achievers and those who are considered as high achievers. So-called low achievers are normally left behind following conventional instruction. Instead, under modeling instruction, they are enabled to complete their courses with above average performance.

Transportability to other courses. Inquiry skills, tools and learning styles that students develop under modeling instruction are stable and generic. Students take advantage of them to excel in their study when taking subsequent science courses, irrespective of whether or not modeling instruction is followed in these courses.

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